LA-UR-20-21645

Approved for public release; distribution is unlimited.

Title:	Comparison of Light-Weight Radioisotope Heater Unit (LWRHU) Historical Testing to Special Form Testing Requirements
Author(s):	Ricketts, Thomas Edgar Eaton, Stacey Lee Armstrong, Megan Jean
Intended for:	Report
Issued:	2020-02-20

Comparison of Light-Weight Radioisotope Heater Unit (LWRHU) Historical Testing to Special Form Testing Requirements

January 2020

Prepared by:

Megan Armstrong, NSPI-DO/RPS Design Agency

Stacey Eaton, NSPI-DO/RPS Design Agency

Thomas Ricketts, NSPI-DO/RPS Design Agency

Technical Reviewers:

VICTOR MARTINEZ (Affiliate)

Digitally signed by VICTOR MARTINEZ (Affiliate)
DN: c=US, o=U.S. Government, ou=Department of Energy, 0.9.2342.19200300.100.1.1=89001000470248, cn=VICTOR MARTINEZ (Affiliate)
Date: 2020.02.05 10:40:53 -07'00'

Victor Martinez, PF-5 Process Engineer Date
AMPP-1, Heat Source Technologies

JONATHAN TEAGUE (Affiliate)

Digitally signed by JONATHAN TEAGUE (Affiliate)
Date: 2020.02.06 12:07:49 -07'00'

Jonathan Teague, Mechanical Engineer, PE Date
E-1, Mechanical and Thermal Engineering Group

Acknowledgements

I would like to thank the following organizations for taking time to review and provide valuable input on this document:

AMPP-1, Heat Source Technologies

E-1, Mechanical and Thermal Engineering

TA55-DO, TA-55 Facility Operations

NSPI-DO, Nuclear Security Production Integration

SB-PF4, Safety Basis

Table of Contents

Executive Summary

This paper compares the Light-Weight Radioisotope Heater Unit (LWRHU) historical testing to Department of Transportation (DOT) Special Form criteria per 49 CFR Part 173, *Shippers-General Requirements for Shipments and Packages*, Section 469, *Tests for special form Class 7 (radioactive) materials* as specified in DOE-STD-1027, *Hazard Categorization of DOE Nuclear Facilities*. Compliance with the aforementioned criteria allows for the exclusion of radioactive sources from the facility's nuclear material inventory.

As part of a new program at Los Alamos National Laboratory (LANL), LWRHUs are planned to be moved into TA-55, PF-5 Power Source Assembly Area (PSAA) for assembly and testing activities. The PSAA Facility is categorized as a low hazard, non-nuclear facility per DOE STD-1027 and is described in TA55-PF-5-FHC-11-001, *Facility Hazard Categorization of the PSAA at PF-5, TA-55*. The Facility Hazard Categorization document states, there must be documentation that radioactive sources are engineered to pass the special form testing specified by DOT in 49 CFR 173.469, *Tests for special form Class 7 (radioactive) materials* or ANSI N43.6, *Sealed Radioactive Sources - Classification*. This paper documents the extensive historical environmental safety testing of the LWRHU and demonstrates its ability to survive potential launch safety accident scenarios. The testing results are used herein to demonstrate through a comparative analysis that the robust design of the LWRHU meets or exceeds the special form testing specifications in 49 CFR 173.469, enabling the LWRHU to be transported and handled in PF-5 in support of testing and assembly program.

1.0 INTRODUCTION

A need has been identified for LANL to test a new type of power source unit utilizing a LANL designed, manufactured and safety-tested Light-Weight Radioisotope Heater Unit (LWRHU). Since the proposed power source assembly will use existing LWRHUs from LANL's inventory, it is proposed that the work be performed in the Power Source Assembly Area (PSAA) in the PF-5 basement at the TA-55 Plutonium Facility. The PF-5 facility is currently categorized as a nonnuclear low-hazard facility per DOE-STD-1027. As such, in order to maintain this category, the *Facility Hazard Categorization of the Power Source Assembly Area at PF-5, TA-55* (TA55-PF5-FHC-11-001) specifies:

> "The PSAA facility must have documentation that the source or prototypes of the source have been tested and passed the tests specified by DOT or ANSI for sealed sources."

This paper will compare the historical testing of LWRHUs to the DOT Special Form 49 CFR 173.469 special form testing criteria and make an equivalency determination.

2.0 BACKGROUND

2.1 PF-5 Description

The Power Source Assembly Area is located in the basement of PF-5 at TA-55. The primary mission of the facility is to perform assembly and testing of new and legacy power source units. Details of the facility operations and configuration can be found in the *Facility Safety Plan for the Power Source Assembly Area at PF-5, TA-55* (TA55-PSAA-FSP-11-001).

PF-5 is currently categorized as a nonnuclear low-hazard facility. The radioactive material in inventory is treated as sealed sources and the material-at-risk (MAR) is considered to be zero. To have the radioactive material excluded from inventory, all heat sources must be encapsulated and engineered to pass the criteria defined in DOE-STD-1027, *DOE Standard: Hazard Categorization of DOE Nuclear Facilities*.

Per DOE-STD-1027, Section 3.1.2, *Treatment of Sealed Sources,* sealed radioactive sources that meet one of the identified testing specifications may be excluded from the facility's radioactive material inventory. The focus of this paper will be with:

- "Department of Transportation (DOT) special form criteria per 49 CFR Part 173, *Shippers – General Requirements for Shipments and Packages*, Section 469, *Tests for special form Class 7 (radioactive) materials*.
- Additionally, "Facilities that exclude material in sealed radioactive sources shall: Maintain records for each excluded sealed source that demonstrates the source is engineered to pass and continues to meet the … special form performance criteria. Examples include … engineering, test, and safety analysis documentation."

2.2 LWRHU Description

Starting in the early 1980s, LWRHUs were manufactured at LANL and qualified to provide thermal power for space missions. The LWRHU was designed to provide approximately one thermal watt of power for up to seven years after fueling. The single 1-watt$_{th}$ unit design provides options in the number and placement of units on a spacecraft to maintain normal operating temperatures for critical instruments and mechanical devices (refer to Figure 1). The unit was designed to meet several safety requirements with regards to impact resistance, temperature resistance, corrosion resistance, and ablation control associated with space vehicle launch and reentry accidents. The LWRHU's robust design assembly consists of the following four components: $^{238}PuO_2$ ceramic fuel pellet, platinum-alloy encapsulation, pyrolytic graphite thermal insulation, and fine-weave pierced fabric (FWPF) aeroshell. (Refer to Appendix 1 for an exploded view of the LWRHU configuration.)

Figure 1. LWRHU graphitic components

The ceramic fuel pellet is encapsulated in containment cladding composed of platinum alloy with 30% rhodium (Pt-30Rh), selected for its high ductility. The cladding material has sufficient strength and ductility to survive earth reentry impact with no release of fuel and has a melting point which will withstand the high reentry temperatures. The fueled capsule is vented and designed to allow the release of helium generated by the alpha decay of the heat source plutonium dioxide (HS-PuO_2) fuel pellet while preventing the release of any particulates from the sintered fuel pellet. The vent is fabricated of sintered platinum powder (3.15 mm diameter and 0.50 mm thick) and electron beam welded to the vent cap. The vent and frit designs were derived from experience with the Multi-Hundred-Watt heat source capsule and have been proven to prevent the release of radioactive material under normal and postulated accident scenarios.

The fueled clad (encapsulated pellet) is then assembled into the pyrolytic graphite thermal insulation layers to provide added insulation during possible earth reentry events. The outermost layer is a graphite composite aeroshell providing high strength at elevated temperatures, excellent resistance to thermal shock, and resistance to catastrophic failure due to brittle fracture.

3.0 PROPOSED ACTIVITY

LWRHUs (fueled clad assembled inside the sealed graphite aeroshell) will be pulled from LANL's current inventory and transferred to PF-5. Once in PF-5, the LWRHUs will be assembled into the next level assembly and tested to validate the design of the new radioisotope thermoelectric generator (RTG). The LWRHU will not be modified during the assembly or testing and will only serve as a source of heat for the power conversion unit. The proposed testing activities of the power unit is comprised of a suite of thermal and mechanical testing, that include thermal vacuum testing, vibration testing, shock testing and a DC resistance check - none of which shall challenge the design of the LWRHU. After completion of the testing, the LWRHU may be removed from the RTG and returned to PF-4. Upon successful testing results, the power supply along with the LWRHU may be shipped off-site.

4.0 SPECIAL FORM TEST REQUIREMENTS

The DOT Special Form testing requirements are specified in 49 CFR Part 173, *Shippers – General Requirements for Shipments and Packages*, Section 469, *Tests for special form Class 7 (radioactive) materials*. Table 1 below summarizes the requirements for each type of test.

Table 1. Special Form Class 7 Test Requirements

Test	Requirement
Impact	• Specimen must fall onto the target from a height of 9 m (30 ft) or greater. The target must be as specified in 49 CFR 173.465(c)(5).
Percussion	• Specimen is placed on a lead sheet and struck by flat face of steel billet so as to produce an impact equivalent to that resulting from a free drop of 1.4 kg (3 lbs) through 1m (3.3 ft)
Bending	• This test applies only to long, slender sources with a length of 10 cm (4 inches) or greater and a length to width ratio of 10 or greater
Heat	• The specimen must be heated in air to a temperature of not less than 800°C (1475°F), held at that temperature for a period of 10 minutes, and then allowed to cool.

The following additional conditions apply:

- A different specimen may be used for each of the tests.
- The specimen may not break or shatter when subjected to the impact, percussion, or bend tests.
- The specimen may not melt or disperse when subjected to the heat test.
- After each test, leaktightness or indispersibility of the specimen must be determined.

Since the LWRHU is designed as a vented fueled capsule within the aeroshell assembly, the leaktightness test specified in 49 CFR 173.469 is not feasible. Thus, the indispersibility test using the leaching assessment by immersion, shall be evaluated.

5.0 HISTORICAL LWRHU TESTING

Extensive testing was performed on the LWRHU during development and prior to its use on the Galileo mission (launch date: October 1989) and the Cassini mission (launch date: October 1997). The units tested were of the same design and specifications as those units currently in LANL's inventory and that are proposed for the PF-5 PSAA testing. To demonstrate fuel containment, LWRHUs were subjected to various tests that simulated the thermal and mechanical environmental assaults postulated for spacecraft accidents on the launch pad and reentry aborts. Briefly, the type of tests performed were the following:

- Impact:
  - Multiple Isotope Fuels Impact Tester (IFIT) campaigns were performed at LANL on the clad and assembly with velocities ranging between 21 to 128 m/s. All units survived without breaching or contamination release.
  - Two assemblies were each impacted repeatedly with increasing velocities of 20 to 50 m/s in increments of 10 m/s, with no breaches or contamination detected.
- Fragment (Percussion test equivalent):
  - Seven LWRHU assemblies were impacted by an 18 gram Al-alloy bullet at velocities ranging from 305 to 914 m/s. It was determined that a LWRHU will survive a projectile impact of up to 750 m/s without a contamination release.
- Solid Rocket Propellant Fire (Heat test equivalent):
  - An LWRHU assembly was exposed to a 10.5 minute solid rocket propellant fire at 2,060 °C. Though there was significant damage to the outer assembly, it remained intact with no breach of the radioactive material containment.
- Overpressure (No 49 CFR173.469 equivalent):
  - In two tests, four LWRHU assemblies with vented fueled capsules had their response evaluated to blast effects using a shock tube 18.3 m long with a 305 mm bore. The blast wave was generated using 73.5 kg composition C-4 explosive. It was determined that the static impulse was approximately 38.6 kPa·sec at the target location. It was estimated that the simulant fueled capsule was moving toward the catch box at a velocity of 1,310 m/s. This test showed that the fuel containment capability of the LWRHU fuel capsule is not impaired by the overpressure environment. One capsule did show a breach around the closure weld area as a result of incomplete weld penetration. It was noted, however, that exposure to this type of environment will remove the graphitic layers of protection.
- Seawater Immersion (No 49 CFR173.469 equivalent):
  - Two LWRHU assemblies with vented fueled capsules were exposed to seawater for approximately 1.75 yrs. One was exposed at a depth of 10 inches and the second was exposed at a pressure of 68.9 MPs (10,000 psi), the equivalent of 6,000 m ocean depth. In neither situation was there evidence of a reaction between the seawater and the fueled capsules (Pt-30Rh) or between the seawater and the $^{238}PuO_2$ fuel pellet.

The details of each of these tests can be found in the listed references (LA-9078-MS, LA-10352-MS, LA-13311-MS, and LA-13339-MS).

6.0 TEST RESULTS COMPARISON

The following sections describe in detail the previous LWRHU safety testing that was performed, the results of the tests, and how they meet or exceed the DOT Special Form testing requirements. For easy reference, refer to Appendix 2, *Comparison of Impact Test Results to Special Form Requirements Summary,* and Appendix 3, *Comparison of Percussion, Bending, and Heat Test Results to Special Form Requirements Summary,* for tables summarizing the comparisons.

6.1 Impact Testing

The 49 CFR 173.469 section for the impact test requirement states that the specimen needs to fall from at least 9 m onto a target. An object falling from 9 m would have a final velocity of approximately 13.3 m/s on impact. In LA-10352-MS, *Environmental Safety Analysis Tests on the Light Weight Radioisotope Heater Unit*, six impact tests are described. Each test was done on an aeroshell assembly containing a vented $^{238}PuO_2$ fueled clad and tested in LANL's IFIT facility. Two of the units tested were aged 2.5 years, while the other four were considered "as built." The impact velocities of these six tests were all at an approximate velocity of 49 m/s and at various impact orientations. The impact velocity for these tests is substantially greater than the CFR required velocity of 13.3 m/s. The graphite components were significantly damaged, but there was little to no damage to the fuel capsule because the graphite protected the fueled capsule (refer to Figure 2). Based on contamination smears associated with the IFIT system and metallography results, no breach in the encapsulation was noted in any of the six tests.

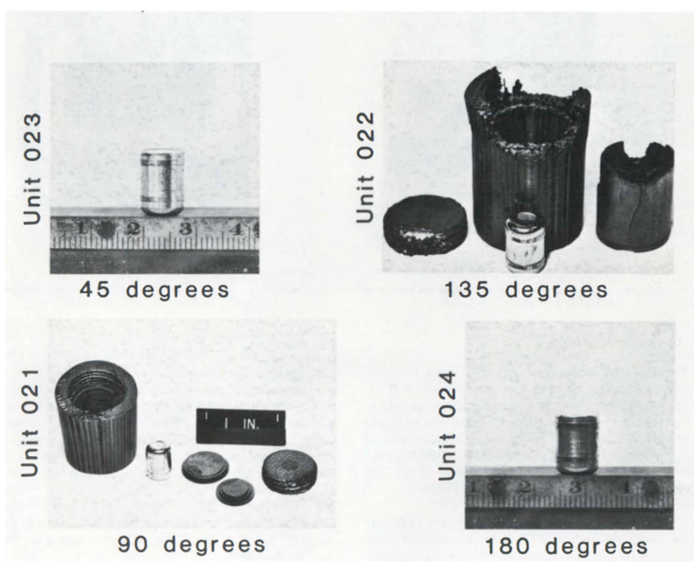


Figure 2. As built LWRHUs after impact at 49 m/s.

As described in the same report, seven other impact tests were conducted on just the LWRHU $^{238}PuO_2$ vented fueled capsules (no graphite components). Three of the capsules were tested at 0°, 45°, and 90° orientation at 48 m/s. The rest of the capsules were tested at a 90° orientation and at velocities of 68, 88, 105, and 128 m/s. None of the capsules failed, proving the capsule provides substantial containment capability during various impact scenarios.

LA-13311-MS, *Light Weight Radioisotope Heater Unit Production Qualification Impact Test*, describes a single impact test of a vented Cassini LWRHU. The test was performed on an assembly containing a $^{238}PuO_2$ fuel pellet and tested in LANL's IFIT facility. The test article was impacted at ambient temperature against a hardened steel target at 53.5 m/s at a side-on orientation. The recovered aeroshell was still intact (refer to Figure 3). The survey smears of the test components had no detectable radioactivity. The results were compared to a previous impact of a LWRHU fabricated for the Galileo mission. In both cases, the Pt-30Rh fuel capsule maintained its integrity and the fuel was completely contained while the aeroshell sustained minimal deformation.

Figure 3. Disassembled Cassini LWRHU after impact at 53.5 m/s.

LA-13339-MS, *Light Weight Radioisotope Heater Unit Sequential Impact Test*, describes sequential impacts on two vented LWRHUs. The tests were performed on assemblies containing a simulant fuel pellet (depleted uranium) and tested in LANL's IFIT facility. The test articles were impacted at ambient temperature against a hardened steel target at ~20 m/s, one at side-on and one at end-on impact orientation. The aeroshell remained intact. The survey smears of the test components had no detectable radioactivity; this indicates the fuel capsule maintained its integrity and the Urania fuel was contained by the capsule. The same test was then repeated on the same assembly, but at impact velocities of 30 m/s, then at 40 m/s, and finally at 50 m/s. In all the remaining cases, smear surveys of the test components had no detectable radioactivity, indicating the simulant fuel was contained by the capsule.

As discussed previously, per 49 CFR 173.469, leaktightness or indispersibility of the specimen must be determined after each of the specified tests. Since the fuel capsule is vented, a leaktightness test could not be performed. Additionally, the indispersibility (immersion) determination after each test was not performed during any historical testing. However, referencing ISO 9978, *Sealed Radioactive Source - Leakage Test Methods*, Table 1, "Threshold detection values and limiting values for different techniques", a wipe test (smear survey) has equivalent sensitivity to the immersion test. The wipe test can be used as a leaktightness indicator in cases where no other test is more suitable. Refer to Appendix 4, *Threshold Detection Values*, for a copy of Table 1. Since no contamination was detected by the smear surveys, it can be concluded that the impacted assemblies met the indispersibility requirement.

Thus, the LWRHU can survive impact environments exceeding the impact testing requirements identified in 49 CFR 173.469 and still meet the indispersibility requirement.

6.2 Percussion Testing

The 49 CFR 173.469 requirements for percussion testing consist of placing the specimen on a lead sheet supported by a smooth solid surface. Then, using the flat face of a steel billet, the billet must strike the specimen with a force that is at least the equivalent of a free drop of 1.4 kg through 1 m. The flat face of the billet has to be 2.5 cm in diameter with 3 mm ± 0.3 mm radius rounded edges.

No percussion testing has been done on the LWRHU assembly that matches this requirement. Rather, significant bullet/fragment tests have been conducted to simulate fragments of a space shuttle impacting an LWRHU. As discussed in LA-10352-MS, .50-caliber bullets were machined out of special aluminum alloy (2216-T87), weighing 18 g, to replicate pieces of the space shuttle's external tank. The diameter of the bullet was 1.3 cm in diameter, which is almost half of the required diameter of the percussion test billet. The bullet was 5.1 cm in length with a beveled impact surface. As part of the seven tests performed, these bullets were fired at a vented simulant-fueled LWRHU assemblies at velocities ranging from 305 m/s to 914 m/s. Smear surveys of the test components showed no detectible radioactivity, and evaluation of the longitudinal metallography sections demonstrated that the fueled capsule had deformed, but did not breach (refer to Figure 4). It was concluded that the LWRHU could survive fragment impacts of velocities greater than 750 m/s, but less than 900 m/s without breaching.

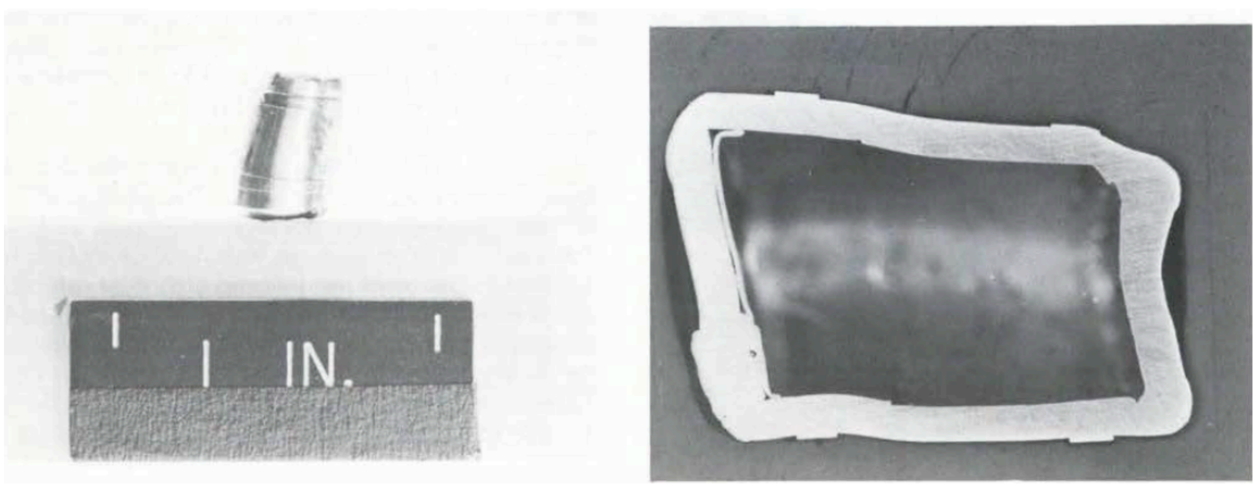


Figure 4. LWRHU fueled clad profile and longitudinal metallographic section after bullet impact at 661 m/s.

When comparing the energy transferred during both of these tests, the fragment testing at the lowest velocity (305 m/s) impacts with a kinetic energy of ~835 Joules. The kinetic energy from the percussion testing criteria identified in 49 CFR173.469 is approximately 14 Joules.

According to 49 CFR 173.469, leaktightness or indispersibility of the specimen must be determined after each of the specified tests. Since the fuel capsule is vented, a leaktightness test could not be performed. Additionally, the indispersibility (immersion) determination after each test was not performed during any historical testing. However, referencing ISO 9978, *Sealed Radioactive Source - Leakage Test Methods*, Table 1, Threshold detection values and limiting values for different techniques, a wipe test (smear survey) has equivalent sensitivity to the immersion test. The wipe test can be used as a leaktightness indicator in cases where no other test is more suitable. Refer to Appendix 4, for a copy of Table 1. Since no contamination was detected, by smear, it can be concluded that the percussion test passed the indispersibility requirement.

In conclusion, the LWRHU can survive percussion environments exceeding the percussion testing requirements identified in 49 CFR 173.469 and still meet the indispersibility requirement.

6.3 Bending Testing

The CFR requires a bending test for specimens that are 10 cm or greater in length or with a length to width ratio that is 10 or greater. The LWRHU assembly is 3.2 cm in length and has a length to width ratio that is less than 2. Thus, the bending test does not apply to the LWRHU.

6.4 Heat Testing

The fourth and final 49 CFR 173.469 requirement is the heat test. During this test, the specimen must be heated to a temperature of 800°C or greater in air. This temperature must be maintained for a total of 10 minutes, and then the specimen is allowed to cool. LA-10352-MS describes a solid rocket propellant fire test. This test consisted of exposing a vented simulant-fueled LWRHU assembly to the burning of 1,588 kgs of UPT-3001 solid rocket propellant for a duration of 10.5 minutes. The LWRHU was exposed to a temperature of approximately 2,060°C, which is significantly greater than the required minimum temperature for the heat test.

After the solid rocket propellant fire test, the aeroshell assembly was intact with some erosion (refer to Figure 5). When checking the exterior of the unit, no α-activity was detected. The outer and middle pyrolytic graphite insulator bodies had no changes. At the exposed temperature, the inner insulator body did react with the fuel capsule creating a Pt/Rh-C eutectic (refer to Figure 6). The capsule's wall thickness was reduced by 40% of its original thickness. It was concluded that even though the integrity of the unit had been reduced, the aeroshell maintained it integrity and there would be no gross fuel dispersal as long as the unit was handled with reasonable care after an exposure to fire.

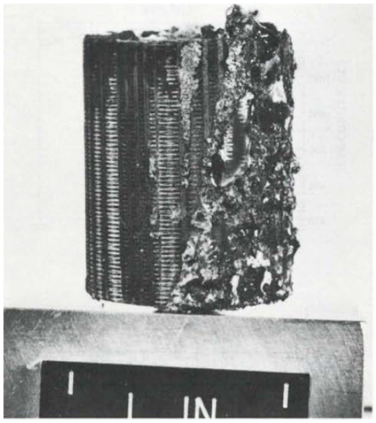


Figure 5. LWRHU aeroshell after being exposed to propellant fire.

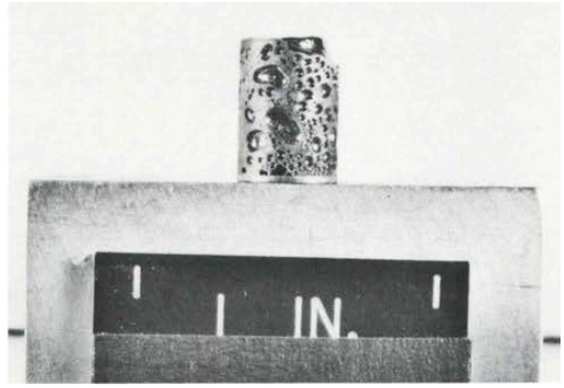


Figure 6. Inner graphite insulator tube showing reaction with capsule.

According to 49 CFR 173.469, leaktightness or indispersibility of the specimen must be determined after each of the specified tests. Since the fuel capsule is vented, a leaktightness test could not be performed. Additionally, the indispersibility (immersion) determination after each test was not performed during any historical testing. However, referencing ISO 9978, *Sealed Radioactive Source - Leakage Test Methods*, Table 1, Threshold detection values and limiting values for different techniques, a wipe test (smear survey) has equivalent sensitivity to the immersion test. The wipe test can be used as a leaktightness indicator in cases where no other test is more suitable. Refer to Appendix 4, for a copy of Table 1. Since no contamination was detected, by smear, it can be concluded that the heat test passed the indispersibility requirement.

In conclusion, the LWRHU can survive temperature environments exceeding the heat testing requirements identified in 49 CFR 173.469 and still meet the indispersibility requirement.

7.0 ADDITIONAL INFORMATION

7.1 PF-4 Safety Analysis

LWRHUs are categorized in the TA-55 Documented Safety Analysis (TA55-DSA-2018) and SDD-TA55-CONT-009, *TA-55 Containers System Design Description* as encapsulated heat sources. As discussed in these documents, because of their robust design, they are designated as safety-class structures, systems and components within the TA-55 Plutonium Facility (PF-4). Their safety function is to provide containment of the plutonium during normal operations as well as impacts associated with a Performance Category (PC)-3 evaluation-basis earthquake and thermal insult from an evaluation basis fire. The encapsulated heat source provides a damage ratio (DR) of zero during and after the evaluation basis accident scenario. The historical test results referenced in technical reports LA-13311-MS and LA-9078-MS, are cited in the TA-55 DSA safety evaluation as evidence that the LWRHUs can withstand the postulated PF-4 accident scenarios.

7.2 Recent LWRHU Surveillance Results

Approximately 134 and 180 heater units were manufactured for the Galileo and Cassini space missions, respectively. LWRHUs for the Galileo mission were manufactured in the 1981 – 1984 timeframe while LWRHUs for the Cassini mission were manufactured in 1995. Today, there are 70 LWRHU existing in LANL's inventory: 59 from the Cassini and 11 from the Galileo manufacturing campaigns. Nine (9) from the Cassini era were recently pulled from inventory for characterization with the following designated pedigree: four flight-quality and five Engineering Use. Several characterization and surveillance activities were performed on the units to determine their current condition. The test results were as follows:

- Aeroshell visual examination
  - No anomalies noted
- Aeroshell radiological contamination surveys
  - No Detectable Activity (NDA) noted
- Aeroshell dose measurements
  - No anomalies noted
- Calorimetry
  - No anomalies noted with initial wattages decayed/calculated to current date vs. current measured value
- Computerized tomography
  - No anomalous condition observed
    - Graphite aeroshell/insulator tubes inspected
    - Shadowgraph of fueled capsule
- Digital radiography
  - No capsule degradation observed
    - Evaluated clad general condition/wall thickness
    - Minimal cracking noted with ceramic fuel pellet

The characterization results discussed above are available, and a summary of results can be found in LA-UR-20-20685, *Cassini LWRHU Characterization and Surveillance.* In addition, in November 2019, one of the flight-quality Cassini LWRHUs was impacted in LANL's IFIT facility to complement the characterization and surveillance activities in determining the integrity of the existing LWRHUs in inventory. Details of the impact can be found in PA-PLAN-01596, *LWRHU Impact Test Plan.* The impact test performed was comparable to that performed in May 1997 (LA-13311-MS, *LWRHU Production Qualification Impact Test*). The preliminary impact test results were obtained during the inner catch tube disassembly. No contamination was noted in the catch tube indicating that the LWRHU containment cladding maintained its integrity.

Also, during disassembly minimal aeroshell deformation was noted (refer to Figure 7), and based on visual inspection, there was no apparent deformation or loss of integrity associated with the fueled capsule (refer to Figure 8). These preliminary results indicate that after 24 years, aging does not appear to be of concern with regards to the aeroshell and fuel capsule integrity. The results are documented in LA-CP-20-20053, *LWRHU Quick-look Impact Test Report*. Further evaluation of the LWRHU fuel capsule containment and fuel particle size analysis will be performed.

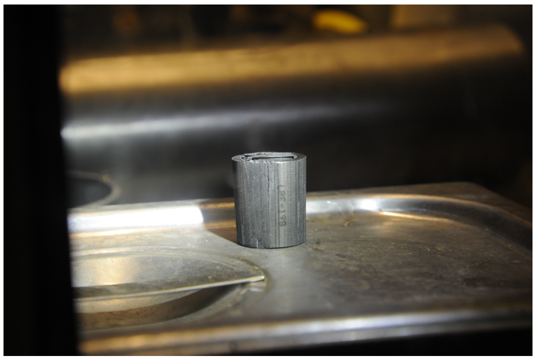


Figure 7. LRF-198 aeroshell exterior after impact.

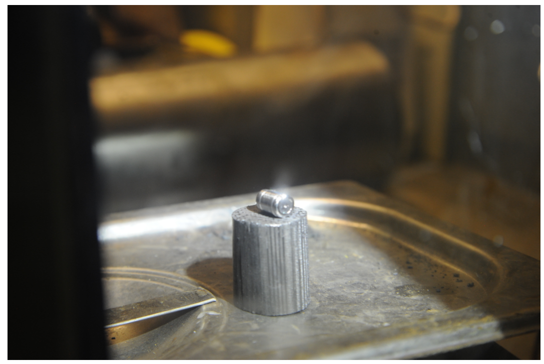


Figure 8. Fueled clad 792, as recovered from aeroshell, after impact.

7.3 Flight Safety Analyses

The National Aeronautics and Space Administration (NASA) has been using LWRHUs as heat sources for their deep space missions for decades, including Galileo (Jupiter), Cassini (Saturn) and the Mars Exploration Rovers. Presidential approval was required for each launch that included nuclear materials. In order to obtain this approval, for each mission an extensive independent safety analysis was performed.

For the analyses, all postulated launch accident scenarios that could adversely affect the LWRHU were considered, including overpressures, fragments and near-pad impacts, propellant fires, full stack intact impact, reentry breakup, out-of-orbit reentry, inadvertent reentry, earth surface impact, and soil burial. The response of the LWRHU to these scenarios is analyzed, supported heavily by the extensive testing described previously. The analyses are documented in Final Safety Analysis Reports (FSARs), which also discuss any possible release of plutonium dioxide and the expected probability, consequence, and risk of such release. Refer to the Cassini mission (MLM-3826, dated February 1997) and Galileo mission (MLM-3540, dated October 1988) FSAR for further details.

In each case, the launch was approved and the LWRHUs were deemed able to adequately and safely withstand postulated accident scenarios within acceptable levels of probabilities and uncertainties.

8.0 CONCLUSION

Through comparative analysis, the LWRHU has clearly demonstrated the equivalence to the special form capsule criteria defined in 49 CFR 173.469, *Tests for special form Class 7 (radioactive) materials* and therefore meets the requirements identified in DOE-STD-1027, *Hazard Categorization of DOE Nuclear Facilities*.

Additionally, the LWRHU was not only evaluated for impact, percussion, heat test and indispersibility as specified by 49 CFR 173.469, but additional historical tests were performed further demonstrating the robustness of the LWRHU. The two additional tests (for which there is no 49 CFR 173.469 equivalence) include the overpressure and seawater immersion test discussed in Section 5.0 of this paper. Further test details can also be found in LA-10352-MS.

Demonstrating that the LWRHU historical safety testing meets the intent of the special form testing requirements in 49 CFR 173.469 and the criteria identified in DOE-STD-1027, the LWRHU is able to be excluded from the PF-5 facility's radioactive material inventory. This will allow the LWRHU to be transferred into the PF-5, PSAA for assembly and testing activities without affecting the existing hazard categorization of PF-5.

9.0 ACRONYMS

Term	Definition
DOT	Department of Transportation
DR	Damage Ratio
DSA	Documented Safety Analysis
FSAR	Final Safety Analysis Report
FWPF	Fine Weave Pierced Fabric
IFIT	Isotope Fuels Impact Tester
LANL	Los Alamos National Laboratory
LWRHU	Light-Weight Radioisotope Heater Unit
MAR	Material-at-Risk
NASA	National Aeronautics and Space Administration
PC	Performance Category
PSAA	Power Source Assembly Area (PF-5)
Pt-30Rh	Platinum alloy with 30% Rhodium
RTG	Radioisotope Thermoelectric Generator

10.0 REFERENCES

Document Number	Title
49 CFR 173.469	*Tests for special form Class 7 (radioactive) materials*
DOE-STD-1027	*DOE Standard for Hazard Categorization of DOE Nuclear Facilities*
ISO 9978	*Sealed Radioactive Sources – Leakage Test Methods*
LA-9078-MS	*The Light Weight Radioisotope Heater Unit (LWRHU): A Technical Description of the Reference Design*
LA-10352-MS	*Environmental Safety Analysis Tests on the Light Weight Radioisotope Heater Unit (LWRHU)*
LA-13311-MS	*Lightweight Radioisotope Heater Unit (LWRHU) Production Qualification Impact Test*
LA-13339-MS	*Light-weight Radioisotope Heater Unit (LWRHU) Sequential Impact Tests*
LA-CP-20-20053	*LWRHU Quick-look Impact Test Report*
LA-UR-20-20685	*Cassini Lightweight Radioisotope Heater Unit Characterization and Surveillance*
MLM-3540	*LWRHU Final Safety Analysis Report for Galileo mission, Volume 1: Introduction and Executive Summary and Reference Design Document*
MLM-3826	*LWRHU Final Safety Analysis Report for the Cassini mission*
PA-PLAN-01596	*LWRHU Impact Test Plan*
TA55-DSA-2018	*TA-55 Documented Safety Analysis*
TA55-PSAA-FSP-11-001	*Facility Safety Plan for the Power Source Assembly Area at PF-5, TA-55*
TA55-PF5-FHC-11-001	*Facility Hazard Characterization of Power Source Assembly Area, PSAA*

11.0 APPENDICES AND ATTACHMENTS

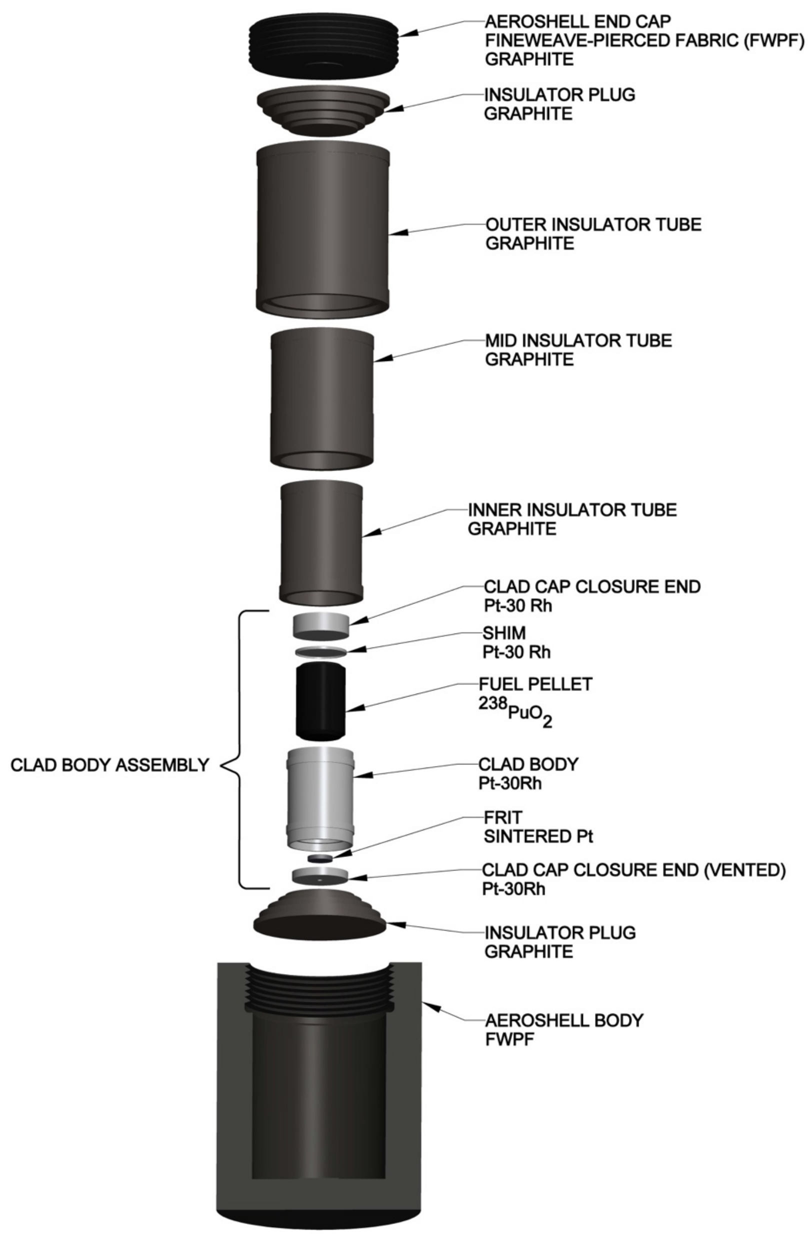
Appendix	Title
1	*Exploded View of the LWRHU*
2	*Comparison of Impact Test Results to Special Form Requirements Summary*
3	*Comparison of Percussion, Bending, and Heat Test Results to Special Form Requirements Summary*
4	*Threshold Detection Values*

Attachment	Title
None	

Appendix 1, LWRHU Exploded View

(Page 1 of 1)

LIGHT-WEIGHT RADIOISOTOPE HEATER UNIT (LWRHU)



Appendix 2, Comparison of Impact Test Results to Special Form Requirements Summary

(Page 1 of 1)

Test	CFR Requirement	Test Performed	Results	Conclusion
Impact	Specimen must fall onto target from a height of 9 m (30 ft) or greater.	Impact: Six (6) LWRHUs assemblies with $^{238}PuO_2$ fuel pellets were impacted in the Los Alamos Isotope Fuel impact Tester (IFIT). Four samples were considered "as builts" and two were approximately 2.5 years old. Nominal impact velocity was 49 m/s, various orientations and various angles. Prior to impact, each capsule removed from graphite components heated to simulate a reentry event.[1], [4]	Significant damage to graphite components. Little to no damage or distortion to the fuel capsules - graphite provides considerable protection. No breach occurred with any of the tested units, based upon radiological smears and metallography.[1]	Safety analysis tests on capsules with graphite protection demonstrated that the ductile Pt-30Rh alloy capsule provides excellent fuel containment capability.[1] Calculation equivalency: CFR requirement of 9m free fall, calculated velocity is 13.3 m/s. LANL historical test perform on aeroshell at approximately 50 m/s with no breach in containment. Also, test were performed just on the capsule at velocities ranging from 50 to 128 m/s with no rupture of the Pt-30Rh cladding.
		During engineering development, seven (7) capsules with 238PuO2 fuel pellet were impacted without graphite at 48 m/s in the 0, 45, and 90 degree orientation. Impacts in the 90 degree orientation at successfully higher velocities (68, 88, 105, and 128 m/s) were also performed.[1], [4]	Substantial deformation but without failure, based upon radiological smears.[1] The amount of capsule deformation increased with velocity, but no rupture of the Pt-30Rh clad was observed. [4]	Development test on the bare capsules demonstrated that the ductile Pt-30Rh alloy capsule provides excellent fuel containment capability.[1]
		LWRHU assembly with 238PuO2 fuel pellet impacted in the LANL IFIT at ambient temperature against a hardened steel target at 53.5 m/s. Prior to impact the LWRHU was heated to simulate a reentry event. Impact orientation was side-on.[2]	The recovered aeroshell was intact, and survey smears of the test components had no detectable activity. Observation: small axial indentation on impact face of aeroshell and small amount of glue dislodged from end cap.[2]	Minimal deformation occurred on the aeroshell and fueled capsule, the fuel was entirely contained.[2]
		Two LWRHU assemblies (simulant fuel pellet, depleted uranium) were impacted at ambient temperature against hardened steel target at 21.2 m/s and then sequentially impacted at higher velocities. One test had side-on orientation impact while the test was impacted end-on. The two test articles were then reimpacted at ~30 m/s. The test articles were then reimpacted at ~40 m/s. The test articles were then reimpacted at ~50 m/s [3]	Initial test: The aeroshells were intact, and survey smears of the test components had no detectable radioactivity, indicating fuel contained by capsules. At 30 m/s smear results had no detectable radioactivity. At 40 m/s smear results had no detectable radioactivity. At 50 m/s smear results had no detectable radioactivity. [3]	Sequentially impacting, in both end-on and side-on orientations, resulted in increased damage with each subsequent impact. The test were performed until aeroshells were distorted and out of dimensional specification, the simulant-fueled capsules were not severely deformed, cracked or breached. The simulant fuel was entirely contained. Sequentially impacting of the LWRHU appears to result in slightly greater damage than a single impact at the final impact velocity of 50 m/s. [3]

Reference:

[1] LA-10352-MS Environmental Safety Analysis Tests on the LWRHU (May 1995)
[2] LA-13311-MS LWRHU Production Qualification Test (May 1997)
[3] LA-13339-MS LWRHU Sequential Impact Tests (August 1997)
[4] LA-9078-MS The LWRHU: A Technical Description of the Referenced Design (January 1982)

Appendix 3, Comparison of Percussion, Bending, and Heat Test Results to Special Form Requirements Summary

(Page 1 of 1)

Test	CFR Requirement	Test Performed	Results	Conclusion
Percussion	Specimen is placed on a lead sheet and struck by the flat face of a steel billet so as to produce an impact equivalent to that resulting from free drop of 1.4 kg through 1m. Note: Flat face of billet must be 2.5 cm in diameter with edge rounded off to a radius of 3mm. Billet must strike specimen so as to cause maximum damage.	Fragment test: Seven (7) test performed with 0.50-caliber bullets from special aluminum alloy (2219-T87), used in space shuttle external tank, were fired at simulant-fueled LWRHU assemblies. The bullet weighed 18g and was 2.0 inches in length by a machined impact surface diameter of 0.49 inches. The bullet was fired at velocities ranging from approximately 305 to 914 m/s. [1]	At velocities from 289 to 757 m/s capsules were deformed but not breached. In the two test at the highest velocities, 908 and 940 m/s, no physical remnants of target capsule were found, significant amount of uranium was detected in the graphite debris collected from catch area. Uranium in posttest debris is interrupted as failure of the containment capability of the capsule. [1]	Based on the results from five of the seven tests, the LWRHU assemblies mounted on magnetometer ring can survive impact by an 18 g, 0.50 caliber aluminum bullet at velocities greater than 750 m/s but not as great as 900 m/s. [1] Calculation equivalency: The kinetic energy calculated from CFR requirement of an impact of 1.4 kgs through 1 m is approximately 14 Joules. Whereas, from LANL historical testing, the fragment test of 18 g bullet at a velocity test of 305 m/s is equivalent to ~835 Joules.
Bending	This test applies only to long slender sources with a length 10 cm or greater and a length to width ratio 10 or greater	N/A		The aeroshell dimensions are 25.95 mm diameter x 31.95 mm height. [2] Does not meet length criteria for bend test.
Heat	Specimen must be heated in air to a temperature of not less than 800°C, held at that temperature for a period of 10 minutes, then allowed to cool	Solid Rocket Propellant Fire: A LWRHU (simulant fuel pellet) was exposed to a 10.5-minute fire of burning solid rocket propellant (UPT-3001). For this test, 0.9 x0.9 x 0.9m cube of propellant weighing 1588 kgs was inhibited on five sides and placed on a sand bed -LWRHU placed on sand bed about 5mm from uninhibited propellant-cube face. Thermocouples measured temperatures of ~2,060C out to a distance of at least 1.8 m (6ft).[1]	After the fire test, the aeroshell was intact. The surface that faced the fire was somewhat eroded and encrusted with propellant fire products. No alpha activity was detected on the exterior of the aeroshell. Upon disassembly, the outer and middle pyrolytic graphite insulator bodies were unchanged. The inner insulator body appears to have reacted with the Pt-30Rh fuel capsule, forming a Pt/Rh - C eutectic. The temperatures for Pt-C and Rh-C eutectics are 1705C and 1694C, respectively.[1]	The integrity of the unit has been greatly reduced by exposure to the 10.5 minute propellant fire, but the outer graphite components provided sufficient containment capability.[1]

Reference:

[1] LA-10352-MS Environmental Safety Analysis Tests on the LWRHU (May 1995)
[2] AYD790380 Drawing: Aeroshell Body

Appendix 4, Threshold Detection Values

(Page 1 of 1)

ISO 9978:1992(E)

Table 1 — Threshold detection values and limiting values for different test methods

Test method	Sub-clause	Threshold detection value	Limiting value	
			Non-leachable content	Leachable or gaseous content
		Activity, Bq	kBq	
Immersion test (hot liquid)	5.1.1	10 to 1	0,2	0,2
Immersion test (boiling liquid)	5.1.2	10 to 1	0,2	0,2
Immersion test with a liquid scintillator	5.1.3	10 to 1	0,2	0,2
Gaseous emanation test	5.2.1	4 to 0,4	—1)	0,2 (^{222}Rn/12 h)
Emanation test with a liquid scintillator	5.2.2	0,4 to 0,004	—1)	0,2 (^{222}Rn/12 h)
Wet wipe test	5.3.1	10 to 1	0,2	0,2
Dry wipe test	5.3.2	10 to 1	0,2	0,2
		Standard helium leakage rate, $\mu Pa \cdot m^3 \cdot s^{-1}$		
Helium test	6.1.1	10^{-2} to 10^{-4}	1	10^{-2}
Helium pressurization test	6.1.2	1 to 10^{-2}	1	10^{-2}
Vacuum bubble test	6.2.1	1 2)	1	—3)
Hot-liquid bubble test	6.2.2	1 2)	1	—3)
Gas pressurization bubble test	6.2.3	1 2)	1	—3)
Liquid nitrogen bubble test	6.2.4	10^{-2} 2)	1	10^{-2}
		Mass gain of water, μg		
Water pressurization test	6.3	10	50	—3)

1) Unsuitable.
2) These detection limits are applicable only to single leaks under favourable visual conditions.
3) Not sensitive enough.